NFL-H$_\infty$/SMC 의 안정도 증명 : Part 4

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Stability Proof of NFL-H$_\infty$/SMC : Part 4

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[Abstract] In this paper, a stability proof of the closed-loop stability for the nonlinear feedback linearization-H$_\infty$/sliding mode controller (NFL-H$_\infty$/SMC) is done by a Lyapunov function candidate using an addition form of the sliding surface vector and the estimation error.

Keywords : nonlinear feedback linearization-H$_\infty$/sliding mode controller, separation principle, Lyapunov function, separation principle, stability proof

1. Introduction

The standard Dole, Glover, Khargoneker, and Francis (abbr. : DGKF 1989) H$_\infty$ controller (H$_\infty$C) [1] has been extended to the nonlinear feedback linearization-H$_\infty$/sliding mode controller (NFL-H$_\infty$/SMC) [2-18]. In this paper, the closed-loop stability is proved by a Lyapunov function candidate using an addition form of the sliding surface vector and the estimation error.

2. NFL-H$_\infty$/SMC

The state equations under worst case based on nonlinear feedback linearization (NFL) [19] are

$$z(t) = T(x(t)) \quad (1)$$

$$\dot{z}(t) = Az(t) + B_1 w_{worst}(t) + B_2 u(t) \quad (2)$$

$$p(t) = C_1 z(t) + D_{11} w_{worst}(t) + D_{12} u(t) \quad (3)$$

$$y(t) = C_2 z(t) + D_{21} w_{worst}(t) + D_{22} u(t) \quad (4)$$

The H$_\infty$ estimator state equation based on NFL is [1]

$$\dot{\hat{z}}(t) = A\hat{z}(t) + B_2 u(t) + B_1 \hat{w}_{worst}(t) + Z_\infty K_e \left(y(t) - \hat{y}(t)\right) \quad (5)$$

where $\hat{w}_{worst}(t) = \gamma^{-2} B_1^T X_\infty \hat{z}(t)$ (6)

$$\hat{y}(t) = \left[C_2 + \gamma^{-2} D_{21} B_1^T X_\infty\right]\hat{z}(t) \quad (7)$$

The controller gain K_c is given by

$$K_c = \tilde{D}_{12}\left(B_2^T X_\infty + D_{12}^T C_1\right) \quad (8)$$

where $\tilde{D}_{12} = \left(D_{12}^T D_{12}\right)^{-1}$ (9)

The estimator gain K_e is given by

$$K_e = \left(Y_\infty C_2^T + B_1 D_{21}^T\right)\tilde{D}_{21} \quad (10)$$

where $\tilde{D}_{21} = \left(D_{21} D_{21}^T\right)^{-1}$ (11)

The term Z_∞ is given by

$$Z_\infty = \left(I - \gamma^{-2} Y_\infty X_\infty\right)^{-1} \quad (12)$$

The controller Riccati equation term X_∞ is

$$X_\infty = Ric\begin{bmatrix} A - B_2\tilde{D}_{12}D_{12}^T C_1 & \gamma^{-2}B_1B_1^T - B_2\tilde{D}_{12}B_2^T \\ -\tilde{C}_1^T\tilde{C}_1 & -\left(A - B_2\tilde{D}_{12}D_{12}^T C_1\right)^T \end{bmatrix} \quad (13)$$

where $\tilde{C}_1 = \left(I - D_{12}\tilde{D}_{12}D_{12}^T\right)C_1$ (14)

The estimator Riccati equation term is

$$Y_\infty = Ric\begin{bmatrix} \left(A - B_1\tilde{D}_{21}D_{21}^T C_2\right)^T & \gamma^{-2}C_1C_1^T - C_2^T\tilde{D}_{21}C_2 \\ -\tilde{B}_1\tilde{B}_1^T & -\left(A - B_1\tilde{D}_{21}^T\tilde{D}_{21}C_2\right) \end{bmatrix} \quad (15)$$

where $\tilde{B}_1 = B_1\left(I - D_{21}^T\tilde{D}_{21}D_{21}\right)$ (16)

The estimated control input based on NFL is

$$u_c(t) = -K_c\hat{z}(t) \quad (17)$$

The closed loop system can be expressed as

$$\begin{bmatrix}\dot{z}(t)\\ \dot{\hat{z}}(t)\end{bmatrix} = \begin{bmatrix} A & -B_2K_c \\ Z_\infty K_e C_2 & A_2 \end{bmatrix}\begin{bmatrix} z(t)\\ \hat{z}(t)\end{bmatrix} + \begin{bmatrix} B_1 \\ Z_\infty K_e D_{21}\end{bmatrix} w_{worst}(t) \quad (20)$$

$$\begin{bmatrix}p(t)\\ y(t)\end{bmatrix} = \begin{bmatrix} C_1 & -D_{12}K_c \\ C_2 & 0 \end{bmatrix}\begin{bmatrix} z(t)\\ \hat{z}(t)\end{bmatrix} + \begin{bmatrix} 0 \\ D_{21}\end{bmatrix} w_{worst}(t) \quad (21)$$

where $A_2 := A - B_2K_c + \gamma^{-2}B_1B_1^T X_\infty - Z_\infty K_e\left(C_2 + \gamma^{-2}D_{21}B_1^T X_\infty\right)$ (22)

The state equation based on NFL is

$$\dot{z}(t) = Az(t) + B_1 w_{worst}(t) + B_2 u(t)$$
$$= \left(A + B_1\left(\gamma^{-2} B_1^T X_\infty\right)\right) z(t) + B_2 u(t) \quad (23)$$

The estimation error equation is

$$e(t) = z(t) - \hat{z}(t) \quad (28)$$

The differential estimation error equation is

$$\dot{e}(t) = \dot{z}(t) - \dot{\hat{z}}(t) \quad (29)$$
$$= -\left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e\left(C_2 - \gamma^{-2} D_{21} B_1^T X_\infty\right)\right) e(t) \quad (30)$$

Or, from equation (2), (17) and (23), we get

$$\dot{z}(t) = Az(t) + B_1 w_{worst}(t) + B_2 u(t)$$
$$= \left(A - B_2 K_C\right) z(t) - B_2 K_C e(t) + B_1 w_{worst}(t) \quad (31)$$

The complete closed loop dynamics is

$$\begin{bmatrix} \dot{z}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A - B_2 K_C & -B_2 K_C \\ 0 & A_5 \end{bmatrix} \begin{bmatrix} z(t) \\ e(t) \end{bmatrix} + \begin{bmatrix} B_1 \\ 0 \end{bmatrix} w_{worst}(t) \quad (32)$$

where

$$A_5 := -\left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e\left(C_2 - \gamma^{-2} D_{21} B_1^T X_\infty\right)\right) \quad (33)$$

Theorem 1: Consider the state equations (2-4) based on NFL for the regulation problem under a worst case and the H_∞ estimator (5) based on NFL. The equal controller gain K_{W-SMC}^{equal} and estimator gain $Z_\infty K_e$ under a worst case *may be selected separately* for desired closed-loop behavior.

Proof. To show the separation property of the closed-loop system, the estimation error equation and differential estimation error equation

$$e = z - \hat{z}$$
$$\dot{e} = \dot{z} - \dot{\hat{z}} = Az + B_1 w_{worst} + B_2 \hat{u}_{H\infty/SMC}^{equal}$$
$$-\left[A\hat{z} + B_2 \hat{u}_{H\infty/SMC}^{equal} + B_1 \hat{w}_{worst} + Z_\infty K_e(y - \hat{y})\right]$$
$$= Az + B_1 w_{worst} - A\hat{z} - B_1 \hat{w}_{worst} - Z_\infty K_e y + Z_\infty K_e \hat{y}$$
$$= -\left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e\left(C_2 - \gamma^{-2} D_{21} B_1^T X_\infty\right)\right) e$$
$$\dot{z} = Az + B_1 w_{worst} + B_2 \hat{u}_{H\infty/SMC}^{equal} = Az + B_1 w_{worst} - B_2 K_{W-SMC}^{equal} \hat{z}(e + z)$$
$$= \left(A - B_2 K_{W-SMC}^{equal}\right) z - B_2 K_{W-SMC}^{equal} e + B_1 w_{worst}$$

The complete closed loop dynamics is

$$\begin{bmatrix} \dot{z} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} A - B_2 K_{W-SMC}^{equal} & -B_2 K_{W-SMC}^{equal} \\ 0 & A_5 \end{bmatrix} \begin{bmatrix} z \\ e \end{bmatrix} + \begin{bmatrix} B_1 \\ 0 \end{bmatrix} w_{worst}$$

where $A_5 := -\left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e\left(C_2 - \gamma^{-2} D_{21} B_1^T X_\infty\right)\right)$

The characteristic values is

$$\Delta(s) = \det\begin{pmatrix} sI - A + B_2 K_{W-SMC}^{equal} & -B_2 K_{W-SMC}^{equal} \\ 0 & sI - A_5 \end{pmatrix}$$
$$= \left|sI - \left(A - B_2 K_{W-SMC}^{equal}\right)\right| \cdot \left|sI - A_5\right|$$

The *separation principle* is satisfied. This completes the proof of this theorem. □

The state equation based on NFL under a worst case is

$$\dot{z}(t) = Az(t) + B_1 w_{worst}(t) + B_2 u(t)$$
$$= \left(A + B_1\left(\gamma^{-2} B_1^T X_\infty\right)\right) z(t) + B_2 u(t) \quad (36)$$

The Lyapunov's function candidate is chosen by

$$V(z(t)) = \sigma^2(z(t))/2 \quad (37)$$

The time derivative of $V(z(t))$ can be expressed as

$$\dot{V}(z(t)) = \sigma(z(t))\dot{\sigma}(z(t))$$
$$= G_{SS}^T z(t) G_{SS}^T \dot{z}(t)$$
$$= G_{SS}^T z(t) G_{SS}^T \left[\left(A + B_1\left(\gamma^{-2} B_1^T X_\infty\right)\right) z(t) + B_2 u_{H\infty/SMC}^{equal}(t)\right]$$
$$\leq 0 \quad (38)$$

The control inputs with switching function are

$$u_{H\infty/SMC}^{+}(t) \geq -\left(G_{SS}^T B_2\right)^{-1}\left[G_{SS}^T\left(A + B_1\left(\gamma^{-2} B_1^T X_\infty\right)\right)\right] z(t) \quad \text{for } G_{SS}^T z(t) > 0 \quad (39)$$

$$u_{H\infty/SMC}^{+}(t) \leq -\left(G_{SS}^T B_2\right)^{-1}\left[G_{SS}^T\left(A + B_1\left(\gamma^{-2} B_1^T X_\infty\right)\right)\right] z(t) \quad \text{for } G_{SS}^T z(t) < 0 \quad (40)$$

The control input with sign function is

$$u_{H\infty/SMC}^{sign}(t) = -\left(G_{SS}^T B_2\right)^{-1}\left[G_{SS}^T\left(A + B_1\left(\gamma^{-2} B_1^T X_\infty\right)\right)\right] z(t) sign(\sigma(z(t))) \quad (41)$$

The equation (41) can be simplified as follows:

$$u_{H\infty/SMC}^{sign}(t) = -K_{W-SMC}^{equal} z(t)\ sign(\sigma(z(t))) \quad (42)$$

$$K_{W-SMC}^{equal} := \left(G_{SS}^T B_2\right)^{-1}\left[G_{SS}^T\left(A + B_1\left(\gamma^{-2} B_1^T X_\infty\right)\right)\right] \quad (43)$$

Finally, the *estimated control input vector* is

$$\hat{u}_{H\infty/SMC}^{sign}(t) = -K_{W-SMC}^{equal} \hat{z}(t) sign(\sigma(\hat{z}(t))) \quad (44)$$

subject to, $sign(\sigma(\hat{z}(t))) = 1$ for $\sigma(\hat{z}(t)) > 0$

$sign(\sigma(\hat{z}(t))) = 0$ for $\sigma(\hat{z}(t)) = 0$

$sign(\sigma(\hat{z}(t))) = -1$ for $\sigma(\hat{z}(t)) < 0$

Theorem 2: Consider the state equations based on NFL for the regulation problem under a worst case (2-4) and the H_∞ estimator based on NFL (5). The estimated SMC law with sign function based on NFL is guaranteed an *asymptotically stable* for the system (2)

$$\hat{u}_{H\infty/SMC}^{sign} = -K_{W-SMC}^{equal} \hat{z} sign(\sigma(\hat{z}))$$
$$K_{W-SMC}^{equal} := \left(G_{SS}^T B_2\right)^{-1}\left[G_{SS}^T\left(A + B_1\left(\gamma^{-2} B_1^T X_\infty\right)\right)\right]$$

subject to, $sign(\sigma(\hat{z}(t))) = 1$ *for* $\sigma(\hat{z}(t)) > 0$

$sign(\sigma(\hat{z}(t))) = 0$ *for* $\sigma(\hat{z}(t)) = 0$

$sign(\sigma(\hat{z}(t))) = -1$ *for* $\sigma(\hat{z}(t)) < 0$

Proof. Let us define the estimation error

$$e = z - \hat{z}$$

$$\dot{e} = \dot{z} - \dot{\hat{z}} = Az + B_1 w_{worst} + B_2 \hat{u}^{sign}_{H_\infty/SMC}$$
$$-\left[A\hat{z} + B_2 \hat{u}^{sign}_{H_\infty/SMC} + B_1 \hat{w}_{worst} + Z_\infty K_e (y - \hat{y})\right]$$
$$= Az + B_1 w_{worst} - A\hat{z} - B_1 \hat{w}_{worst} - Z_\infty K_e y + Z_\infty K_e \hat{y}$$
$$= (A - Z_\infty K_e C_2)z - (A - Z_\infty K_e C_2)\hat{z} + B_1 w_{worst}$$
$$-Z_\infty K_e D_{21} w_{worst} - B_1 \hat{w}_{worst} + Z_\infty K_e D_{21} \hat{w}_{worst}$$

Let $\hat{z} := e + z$

$$\dot{e} = (A - Z_\infty K_e C_2)z - (A - Z_\infty K_e C_2)(e + z) + B_1 \gamma^{-2} B_1^T X_\infty z$$
$$-Z_\infty K_e D_{21} \gamma^{-2} B_1^T X_\infty z - B_1 \gamma^{-2} B_1^T X_\infty \hat{z} + Z_\infty K_e D_{21} \gamma^{-2} B_1^T X_\infty \hat{z}$$
$$= -\left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e (C_2 - \gamma^{-2} D_{21} B_1^T X_\infty)\right)e$$

Lyapunov's function candidate and derivative is chosen by

$$V = \frac{1}{2}\sigma^T \sigma + \frac{1}{2} e^T e$$
$$\dot{V} = \sigma^T \dot{\sigma} + e^T \dot{e} = \sigma^T \left(G_{SS}^T \dot{\hat{z}}\right)$$
$$-e^T \left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e (C_2 - \gamma^{-2} D_{21} B_1^T X_\infty)\right)e$$
$$= \sigma^T G_{SS}^T \Big(A\hat{z} + B_2\left(-K^{equal}_{W\text{-}SMC} \hat{z}\, sign(\sigma(\hat{z}))\right) + B_1 \hat{w}_{worst}$$
$$+ Z_\infty K_e C_2 z + Z_\infty K_e D_{21} w_{worst} + Z_\infty K_e D_{22}\left(-K^{equal}_{W\text{-}SMC} \hat{z}\, sign(\sigma(\hat{z}))\right)$$
$$- Z_\infty K_e C_2 \hat{z} - Z_\infty K_e D_{21} \hat{w}_{worst} - Z_\infty K_e D_{22}\left(-K^{equal}_{W\text{-}SMC} \hat{z}\, sign(\sigma(\hat{z}))\right)\Big)$$
$$-e^T \left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e (C_2 - \gamma^{-2} D_{21} B_1^T X_\infty)\right)e$$

Let $w_{worst} = \gamma^{-2} B_1^T X_\infty z(t)$, and $\hat{w}_{worst} = \gamma^{-2} B_1^T X_\infty \hat{z}(t)$

$$\dot{V} = \sigma^T G_{SS}^T \Big(A\hat{z} + B_2\left(-K^{equal}_{W\text{-}SMC} \hat{z}\, sign(\sigma(\hat{z}))\right) + B_1 \gamma^{-2} B_1^T X_\infty \hat{z}$$
$$+ Z_\infty K_e C_2 z + Z_\infty K_e D_{21} \gamma^{-2} B_1^T X_\infty z$$
$$- Z_\infty K_e C_2 \hat{z} - Z_\infty K_e D_{21} \gamma^{-2} B_1^T X_\infty \hat{z}\Big)$$
$$-e^T \left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e (C_2 - \gamma^{-2} D_{21} B_1^T X_\infty)\right)e$$
$$= \sigma^T G_{SS}^T \left[A - B_2 K^{equal}_{W\text{-}SMC} sign(\sigma(\hat{z})) + B_1 \gamma^{-2} B_1^T X_\infty\right]\hat{z}$$
$$+ \sigma^T G_{SS}^T \left(Z_\infty K_e (C_2 + D_{21} \gamma^{-2} B_1^T X_\infty)\right)e$$
$$-e^T \left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e (C_2 - \gamma^{-2} D_{21} B_1^T X_\infty)\right)e$$

Let $K^{equal}_{W\text{-}SMC} := (G_{SS}^T B_2)^{-1}\left[G_{SS}^T (A + B_1 \gamma^{-2} B_1^T X_\infty)\right]$,

$$\dot{V} = \sigma^T G_{SS}^T \Big[A - B_2 (G_{SS}^T B_2)^{-1}\left[G_{SS}^T (A + B_1 \gamma^{-2} B_1^T X_\infty)\right] sign(\sigma(\hat{z}))$$
$$+ B_1 \gamma^{-2} B_1^T X_\infty\Big]\hat{z} + \sigma^T G_{SS}^T \left(Z_\infty K_e (C_2 + D_{21} \gamma^{-2} B_1^T X_\infty)\right)e$$
$$-e^T \left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e (C_2 - \gamma^{-2} D_{21} B_1^T X_\infty)\right)e$$
$$= \sigma^T G_{SS}^T A\left[1 - sign(\sigma(\hat{z}))\right]\hat{z}$$
$$+ \sigma^T G_{SS}^T B_1 \gamma^{-2} B_1^T X_\infty \left(1 - sign(\sigma(\hat{z}))\right)\Big]\hat{z}$$
$$+ \sigma^T G_{SS}^T \left(Z_\infty K_e (C_2 + D_{21} \gamma^{-2} B_1^T X_\infty)\right)e$$
$$-e^T \left(A - \gamma^{-2} B_1 B_1^T X_\infty - Z_\infty K_e (C_2 - \gamma^{-2} D_{21} B_1^T X_\infty)\right)e$$

The estimation error is $e \to 0$ as $t \to 0$.

$$\dot{V} = \sigma^T G_{SS}^T A\left[1 - sign(\sigma(\hat{z}))\right]\hat{z}$$
$$+ G_{SS}^T B_1 \gamma^{-2} B_1^T X_\infty \left(1 - sign(\sigma(\hat{z}))\right)\Big]\hat{z} \le 0$$

subject to,

if $\sigma > 0$, $\quad \dot{V} = 0$
if $\sigma = 0$, $\quad \dot{V} = 0$
if $\sigma < 0$, $\quad \dot{V} \le -2kG_{SS}^T A\hat{z} - 2kG_{SS}^T B_1 \gamma^{-2} B_1^T X_\infty \hat{z} < 0$,

k is positive constant.

The above condition is satisfied on negative definite, and is *asymptotically stable.* This completes the proof of this theorem. □

3. Conclusion

A separation theorem and a stability proof of a nonlinear feedback linearization-H_∞/sliding mode controller (NFL-ROO/SMC) have been done.

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